DESIGN AND FABRICATION OF A THz NANOKLYSTRON

Harish M. Manohara[1], Peter H. Siegel, Colleen Marrese
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA[1]

Baohe Chang, Jimmy Xu
Brown University, Division of Engineering, Providence, RI, USA

ABSTRACT

Recently the authors proposed a novel monolithic tube approach to THz power generation: the nanoklystron. In this presentation they report design and fabrication details of 1200 GHz nanoklystron circuits and ongoing efforts to produce low voltage cold cathodes from carbon nanotube (CNT) emitters. Both silicon-based and metal nanoklystron cavities have now been completed, and measurements on the field emission properties of several CNT cathodes have been made. In addition new techniques for growing highly ordered CNT arrays on flat evaporated surfaces have been demonstrated for the first time. This paper will include analytic design details for the 1200 GHz nanoklystron circuit, fabrication process steps for realizing the monolithic cavity, CNT emission measurements and progress on a UHV cathode and nanoklystron test chamber.

INTRODUCTION

1. Motivation

Millimeter and submillimeter-wave sensor technology has been a major thrust area at JPL for the past ten years. Instruments such as Microwave Limb Sounder, MIRO (Microwave Imager for Rosetta Orbiter), Cloude Ice and Herschel/FIRST have been enabled by the lab's efforts in this area. Future instrument opportunities will necessitate sensors at higher frequencies, greater sampling capability (arrays) and wider spectral (frequency) coverage. For all these applications, as well as for the development of THz communications systems and imagers, strong sources of submillimeter wave power will be required. The most popular technique to produce higher frequency (> 300 GHz) THz power employs low frequency oscillators coupled with nonlinear-reactance based frequency multiplier chains. These suffer from very low efficiencies as the multiplication factor increases (4 and above). The other available techniques such as THz lasers, BWOs (backward-wave oscillators) and carcinotrons are either bandwidth limited or frequency range limited along with being bulky and expensive.

Taking into consideration the above-mentioned issues, a novel approach to realizing a high power output, fixed frequency terahertz source was recently proposed[1, 2], which capitalizes on the current micromachining technology for fabrication. This is called a "nanoklystron." This miniature electron tube (operating as a reflex klystron[3] [Hamilton *et al.*, 1948]) requires an ultra high current density (>1kA/cm^2) field emitter source for the generation of high frequency electron beam.

2. Nanoklystron Operating Principle

A nanoklystron consists of a high-density cathode, bunching tube, RF resonator, shaped repeller and RF output port, all fabricated monolithically on two bonded silicon wafers. Figure 1 shows schematic sketch

[1] *Contact information for H.M. Manohara: Email:Harish.Manohara@jpl.nasa.gov, phone (818) 393-0455*

of such a device. For successful operation of this device a reliable, high current density emission source is of paramount importance. Low operating voltage, low power dissipation, longer operating lifetimes are desirable characteristics of electron sources for this application. In principle, the electrons emitted into the resonating cavity travel across the gap until they are focused back onto themselves by a repelling field at the other end of the gap. The gap in a nanoklystron performs the same function as that of precisely placed grids in a klystron, by producing and sustaining an alternating field from random oscillations in the electron beam. By adjusting the gap potential and the repelling field, electrons can be bunched and properly reflected in phase to couple significant energy to the resonant cavity. In subsequent sections, design considerations and fabrication details for a 1200 GHz nanoklystron are given along with efforts to develop reliable, high current density, carbon-nanotubes-based electron field emitters.

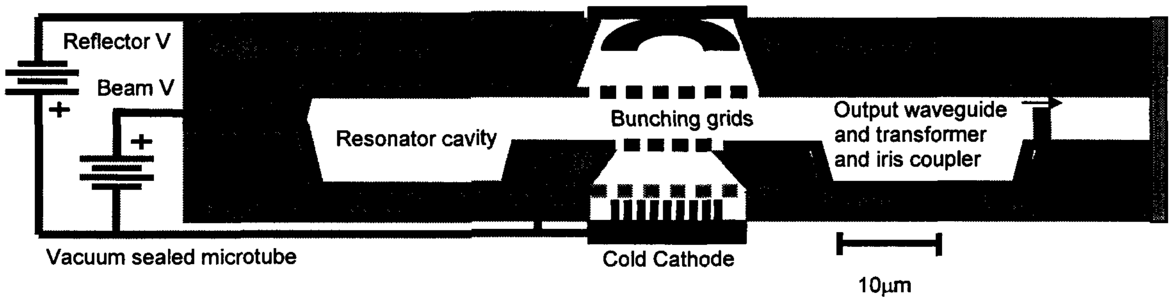

Figure 1. Schematic cross section of a proposed nanoklystron. The cathode is composed of a carbon nanotube field emitter array with integrated grid. The cavity, beam and output waveguide are etched from two silicon wafers, which are later joined by bonding. The repeller and cathode are drop-in parts and vacuum sealing is performed in the last step.

DESIGN AND FABRICATION

1. Design Aspects

A complete analysis has been performed using the original design procedures[4]. The analytic model predicts 50 mW of available power at 1200 GHz from a 3mA beam accelerated to 500V through a 20 μm re-entrant cavity-coupling hole. Cavity losses and iris coupling (loaded Q) cause 47 mW of the available 50mW to be lost in the re-entrant cavity (gold plated walls assumed), leaving approximately 3mW available at the waveguide output port. The simple closed form analysis shows- (1) significant output power is possible with existing cathode current densities and realistic cavity losses (Quickwave was used to simulate the actual cavity resonant frequency and resistive wall loss), and (2) the importance of reducing the cavity parasitic capacitance in order to be able to operate at the highest frequencies. A new cavity layout based on the analysis has now been completed and designs are being implemented.

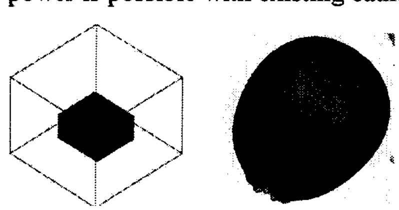

Figure 2. Designed port geometry and predicted output beam pattern with 80% beam efficiency.

Using the above design a new output waveguide geometry that eliminates the need for a full pyramidal horn integrated into the silicon wafer has been conceived. The new output circuit consists of an optimized approximately-half-wavelength-sized aperture that, when coupled with a novel dual offset inverse Cassegrain optical system produces a nice 2 degree RF beam with close to 80% beam efficiency. The design takes advantage of the loading produced by the surrounding silicon wafer on the aperture field distribution in the output port and was checked and optimized with Quickwave. The port geometry (left) and predicted output beam pattern (right) are shown in Figure 2 (without the inverse Cassegrain beam former).

2. Nanoklystron Fabrication

Nanoklystron is fabricated monolithically using silicon micromachining techniques. The top and the bottom halves of the device are etched in silicon separately using deep RIE (DRIE) process and then thermo-compression bonded to form an enclosed resonant cavity. The device consists of a reentrant resonant cavity, an emitter/repeller feedhole, and a step waveguide transformer terminating in silicon lens of half wavelength thickness at the output center frequency (reflection matched) that couples the generated THz power to the outside detector. Using several lithography and DRIE processes, these parts are etched in bulk silicon in two halves and then bonded together to form the required structure. Apertures are etched at the back of the device to allow for the insertion of an electron source (in the bottom half) and a repeller (in the top half). Figure 3 shows SEM micrographs of the top and the bottom halves of a 1200 GHz nanoklystron prior to wafer bonding.

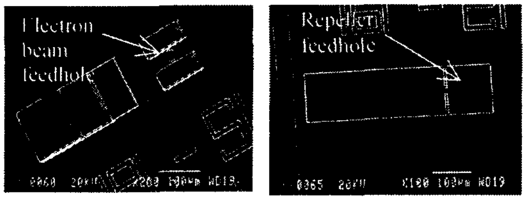

Figure 3. SEM micrographs of top and bottom halves of a 1.2 THz monolithic nanoklystron prior to wafer bonding (α-version)

After the etch step, the top and the bottom halves were coated with chromium, platinum and gold layers of 30, 60 and 250 nm thickness respectively, using e-beam evaporation. The two wafers are then aligned and bonded at a process temperature of 450° C and under a pressure of 2000 N. The total time of bonding was ~3 hours with additional 30 minutes for cooling down. The chamber pressure during bonding was maintained at 1 milliTorr. After bonding, the nanoklystrons were diced into individual devices. Figure 4 shows the cut-view of the bonded cavity and the inset shows the bonded interface at a higher magnification. The bright line indicates fused gold layers and the bond quality was excellent.

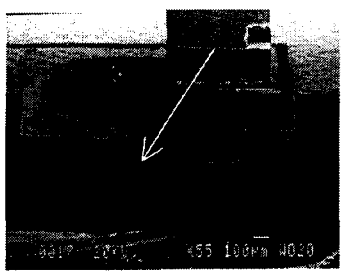

Figure 4. SEM micrographs bonded top and bottom halves of a nanoklystron with the inset showing the bonded interface.

An ultra-high vacuum (UHV) test chamber is being built to test nanoklystrons as well as field emission characteristics of cold cathodes. Initially, nanoklystrons will be tested using conventional hot cathodes that are being designed by commercial vendors.

3. Carbon Nanotube Field Emitters

Electron source for nanoklystrons must be capable of generating current densities of at least 100 A/cm^2. Such current densities at low operating voltages can be generated by employing cold cathodes, especially carbon nanotube-based field emitters. The small diameter of carbon nanotubes (diameter of a single single-walled-nanotube can be <1 nm) enables efficient emission at low fields, despite their relatively high work function (>4.5eV). At 1-3 V/μm of threshold voltage, carbon nanotubes are the best suited for low-power, high-current density applications. Figure 5 shows SEM micrograph of ordered nanotube arrays[5] that are being tested to be used as electron source for nanoklystrons. These nanotubes are grown inside ordered pores of alumina that are produced from the anodization of high-purity aluminum substrates. Typical tip density is about 100 tips/μm^2 with typical tube diameter of ~ 40nm.

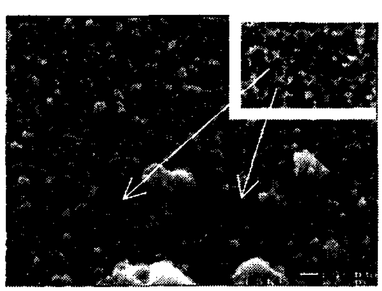

Figure 5. SEM micrographs ordered carbon nanotube array grown inside the ordered pores of alumina. Inset shows the opened CNT tips

To test the emission characteristics of these tips special grids were fabricated. Figure 6 shows SEM micrograph of one such grid structure. The grid is fabricated on silicon with an integrated insulating spacer layer made of hard-baked photoresist. This layer thickness is ~ 1.5 μm. The grid itself is made of gold, 1-μm thick with 2-μm line, 4-μm space mesh (transparency of ~ 45%). The grids were first formed using a lift-off process on a silicon substrate with 0.5 μm of oxide layer on it. This was followed by patterning and hard-baking the spacer layer. In the final step, backside etch was performed using DRIE to open up the beam channel and also to isolate the individual grid structures. By dissolving the oxide layer in BOE (buffered oxide etchant), individual grid chips with suspended mesh were released.

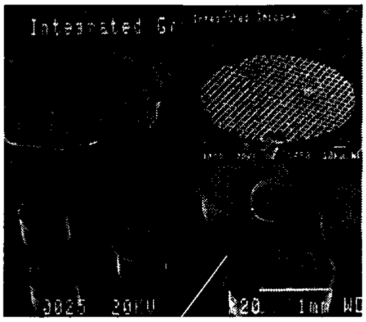

Figure 6. SEM micrographs ordered custom-made grids with inset showing close-up of the gold mesh.

For field emission measurements, a 3 mm × 4 mm piece of the CNT array was hard mounted on a TO5 transistor base. A grid structure was placed on top with its spacer layer facing down and was held in place by non-conductive glue while grid bias contact was made. CNTs were case grounded. Measurements were conducted in a UHV chamber in 7 × 10^{-9} Torr vacuum. Figure 7 shows the variation of emission current (I_g) with respect to grid bias (V_g). Although anode bias voltages of 200 V, 600 V and 800 V were used during the course of the experiment, no anode current was recorded. All of the emission was measured through the grid electrode. Initially, there was a high electron emission at very low V_g. We measured ~ 2.5 μA at 5 V of V_g which increased close to 100 μA at 50 V (inset data). This high current lasted for about ten minutes before dying down. When we restarted the measurements, we could not recover this region again, but consistently measured the second set of data over three different trials (curve that resembles an F-N plot) with a maximum current of ~ 35 μA at V_g =300 V. At this point we had to stop the experiment as the grid and the CNTs short-circuited.

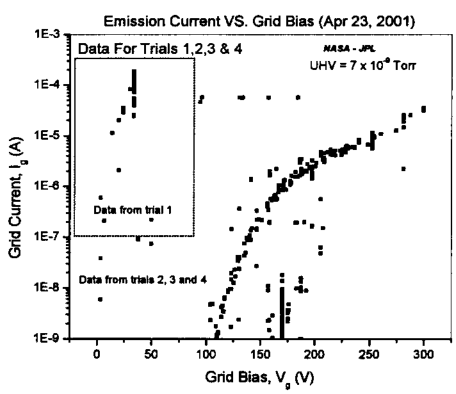

Figure 7. Field emission measurement data of ordered CNT arrays using custom-made grids. Inset data shows the initial burst of emission followed by a data that follows the F-N curves.

CNTs used in this experiment were grown on commercially available high-purity aluminum foils. These foils are highly prone to wrinkles, which make the surface of the CNT sample non-uniform to the order of few tens of microns (as measured by SEM). This results in significant variation of the gap distance between the grid and the CNT surface in spite of having a uniform insulation layer of 1.5-μm thickness. The initial burst of emission at low V_g can be attributed to this surface non-uniformity, which causes a few nanotube tips very close to the grid to emit freely at low biasing potential. It was also noticed that the ratio of emitting tips to the total present was quite low. A sampled count gives ~ 10^8 tips in the emission area of 1 mm dia (0.78 mm^2) and at a projected emission of 300 nA/tip, our emission data accounts for only a few hundreds of tips actually participating in the emission! To eliminate the obvious problems resulting from the non-uniformity of the emitting surface, ordered arrays of carbon nanotubes have been successfully grown on aluminum-deposited, flat, degenerately doped silicon wafers. In the near future emission properties of these samples will be tested. One other major advantage of such CNTs grown on Al-on-Si substrate is their conduciveness for micromachining, which allows for shaping the emitter cross section to any suitable geometry. The emission measurements presented here are very encouraging for applying CNTs as low-operating voltage cold cathodes.

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DESIGN AND FABRICATION OF A 1200 GHZ NANOKLYSTRON

Harish M. Manohara, Peter H. Siegel, Colleen Marrese

Jet Propulsion Laboratory
California institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Jimmy Xu, Baohe Chang

Brown University
Division of Engineering
Providence, RI

OVERALL OBJECTIVE

Develop a milliwatt level, fixed frequency, CW THz source for space borne Earth and planetary remote sensing instruments

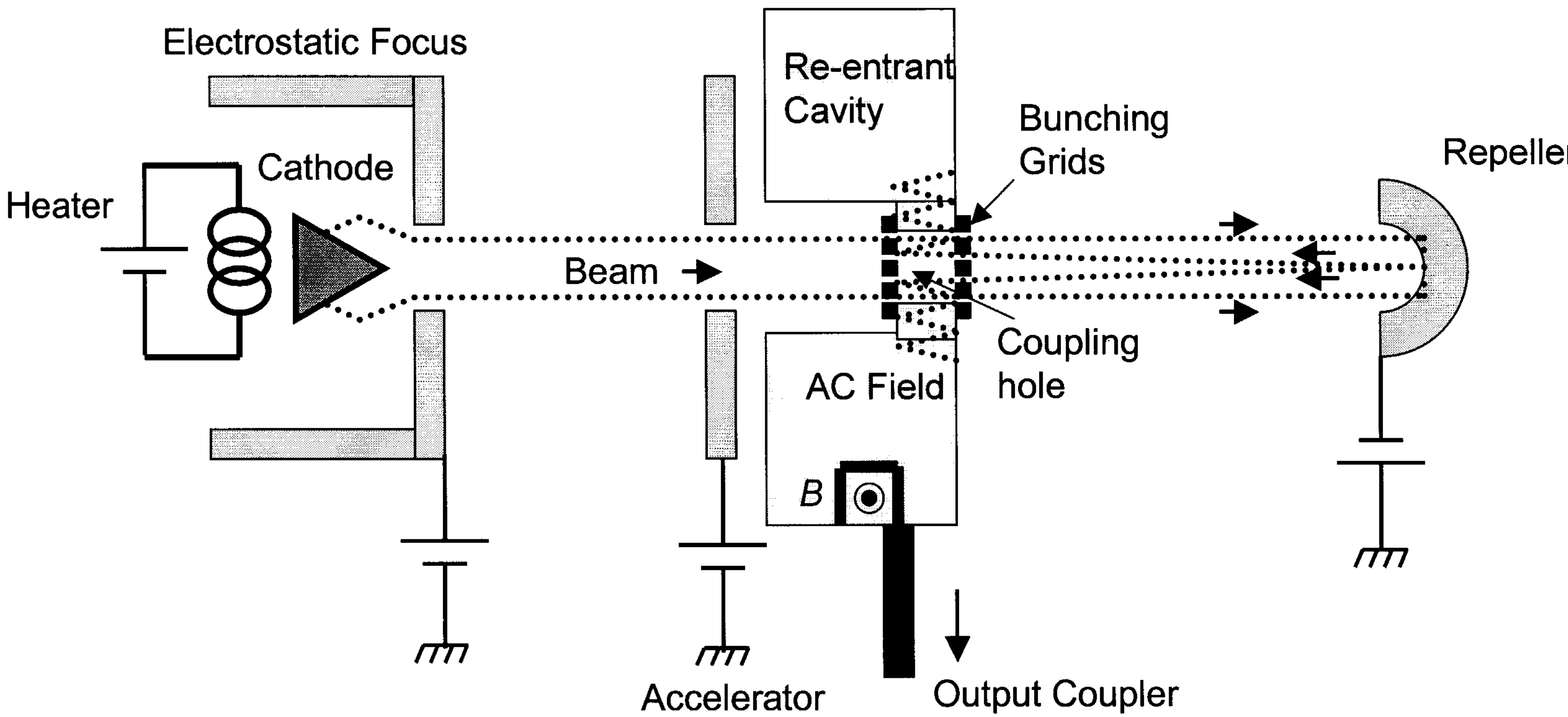
IMPLEMENTATION

Extend vacuum tube reflex klystron oscillator to THz frequencies.

TECHNICAL APPROACH

- ❖**Analyze millimeter-wave klystron performance limitations**
- ❖**Design THz monolithic circuit based on silicon DRIE process**
- ❖**Propose compatible cavity, bunching grid, repeller, output structure**
- ❖**Realize ultra-high current density field-emission cathode**
- ❖**Incorporate built-in low-voltage emitter/focusing grid with cathode**
- ❖**Combine drop-in cathode/grid with cavity/output coupler**
- ❖**Develop high vacuum sealing technique compatible with RF output**
- ❖**Increase power output or frequency agility through array integration**

SCHEMATIC OF A SIMPLE REFLEX KLYSTRON



MODIFICATIONS NEEDED TO REALIZE THZ MONOLITHIC DESIGN

❖ **Physical layout must be made compatible with standard MEMS processing**

Including emitter, re-entrant cavity, focusing electrodes, repeller, output coupler, beam forming antenna

❖ **Split block construction required to allow sculpting of cavities and insertion of wires, focusing electrodes, emitter, repeller**

❖ **Tuning & output Q controllable via simply varied geometric parameters**

❖ **Current densities of existing hot cathodes must be increased dramatically**

MODIFICATIONS NEEDED TO REALIZE THZ MONOLITHIC DESIGN

❖ **Cold cathode operation preferred for space operation and reduced thermal load**

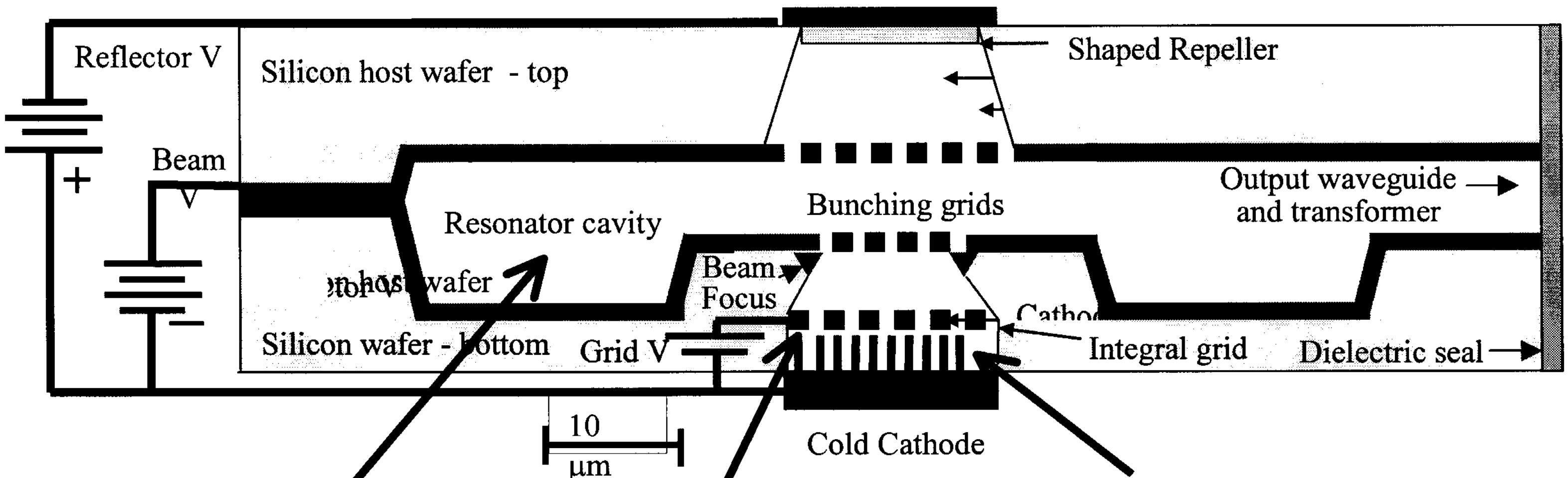
❖ **Cold cathode operation implies integrated emitter grids and extra beam focus**

❖ **Vacuum sealing techniques/window compatible with low RF output loss**

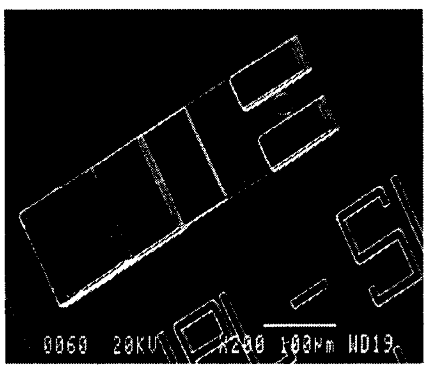
❖ **Early design flexibility needed to allow some trial and error testing**

❖ **Detailed analysis of full circuit and RF beam interactions essential**

SCHEMATIC CONSTRUCTION WITH REALIZED STRUCTURES

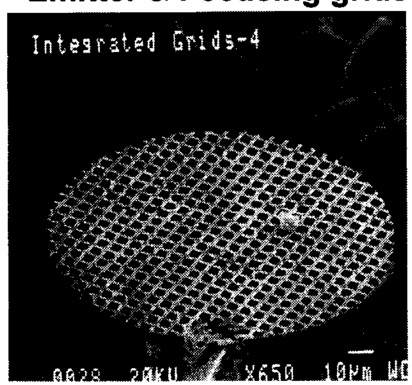


Vacuum sealed split block



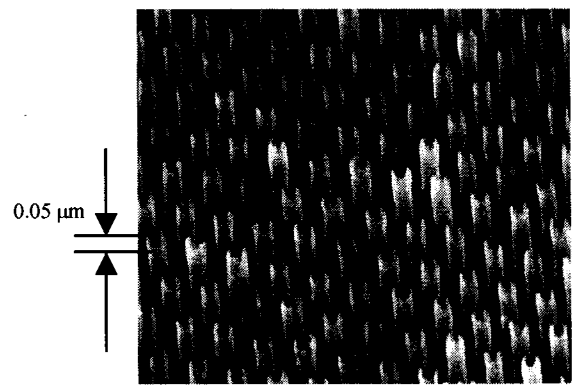
Silicon micromachined cavity (JPL)

Emitter & Focusing grids



Micromachined emitter grid (JPL)

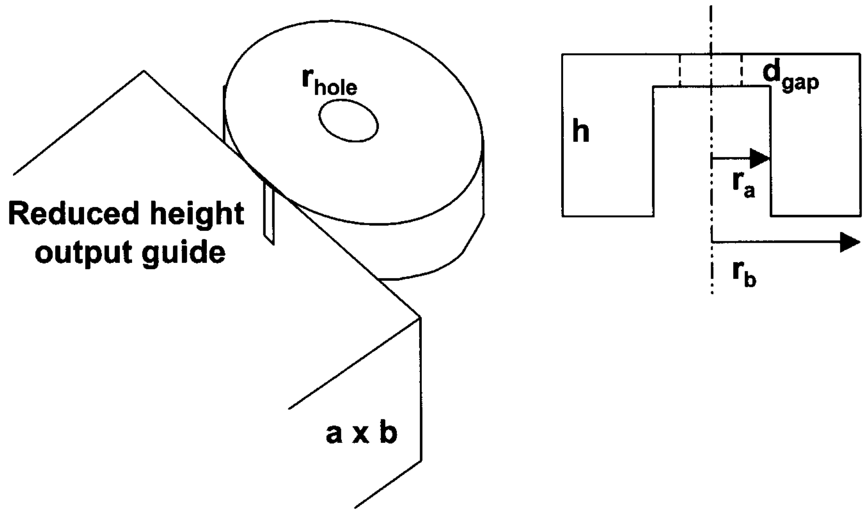
Nanotube or Spindt cathode

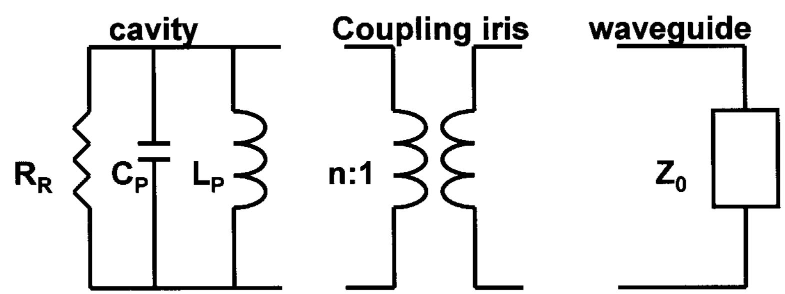


Brown Univ. highly ordered carbon nanotube array (cathode) Li. et.al. APL 75, no.3, Jul 19, 1999

SIMPLIFIED BEAM ANALYSIS FROM J.J. HAMILTON (1958)

Iris-coupled Cylindrical Re-entrant cavity





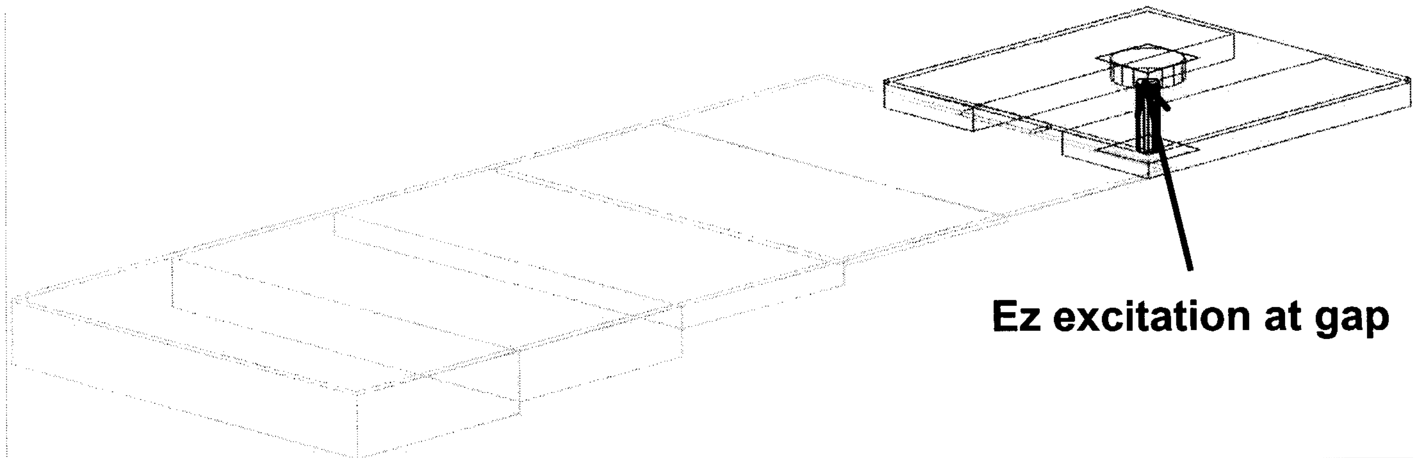
Resonator equiv. circuit

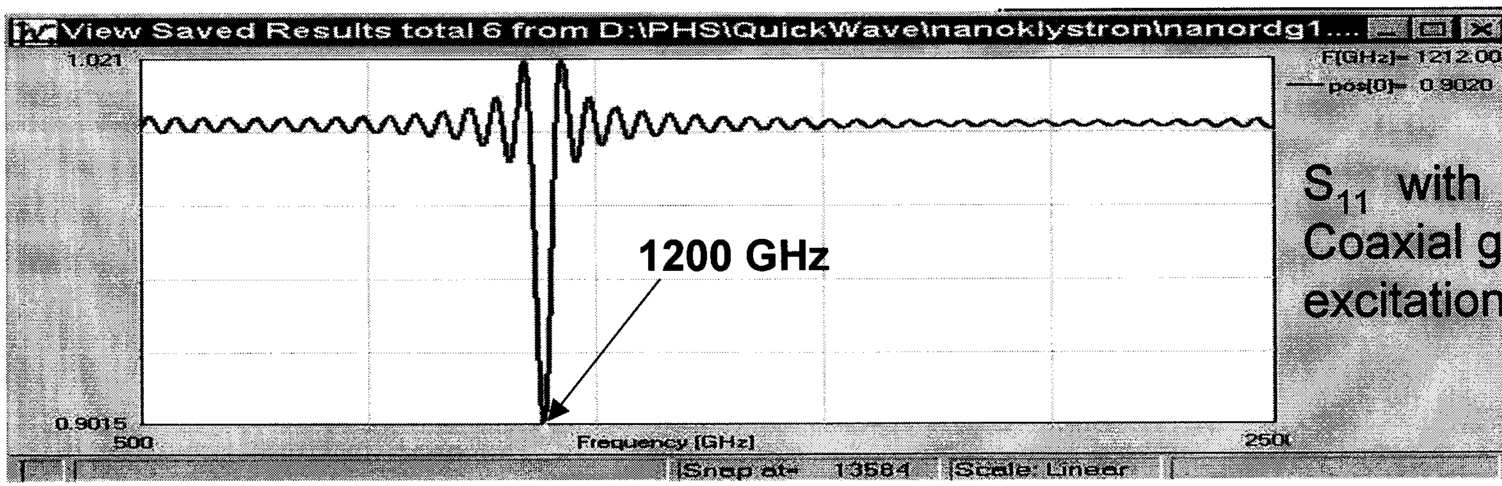
<u>1200 GHz Example</u>

With 500V beam, 3mA current:

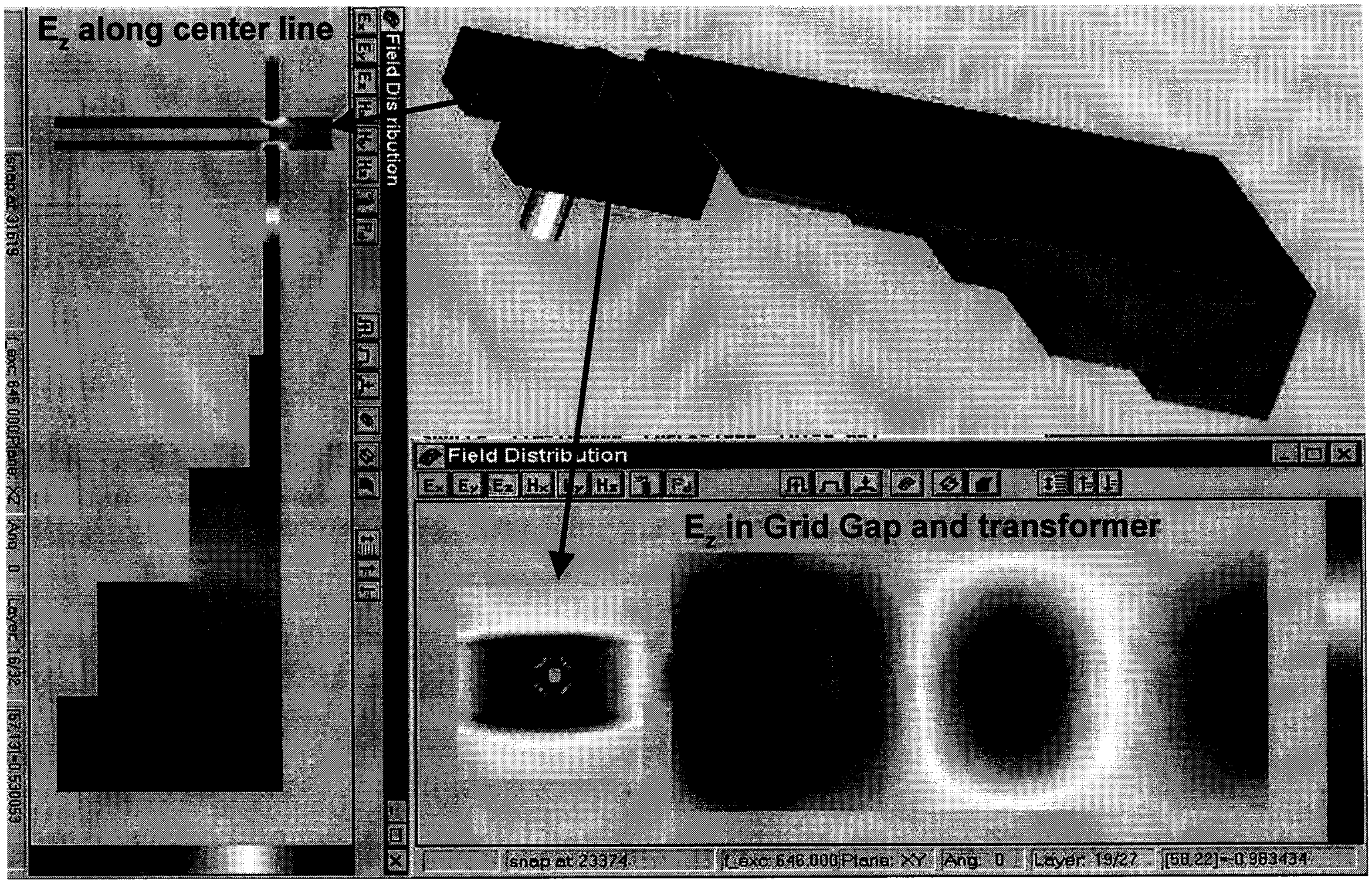
52 mW produced by beam,
49 mW lost in cavity,
3 mW delivered to output load

1200 GHZ RIDGED-WAVEGUIDE RE-ENTRANT CAVITY ANALYSIS FOR NANOKLYSTRON USING QUICKWAVE FDTD

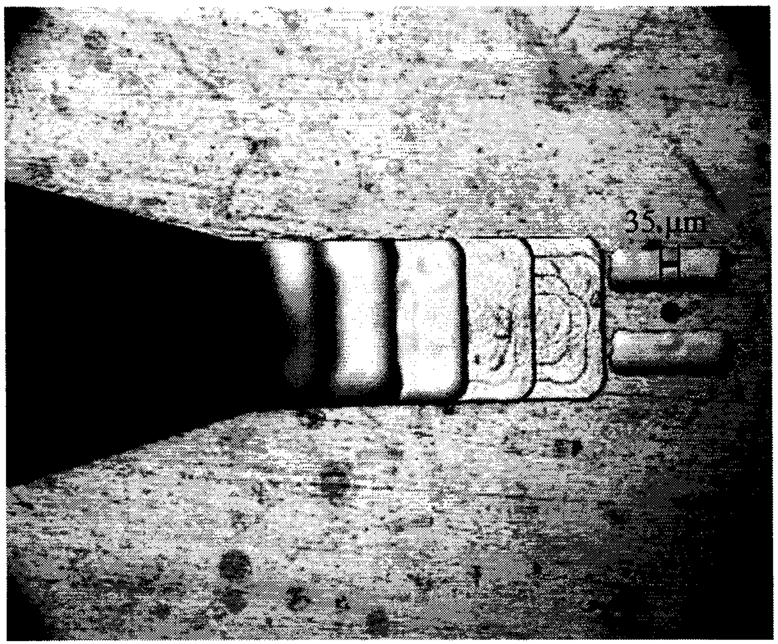


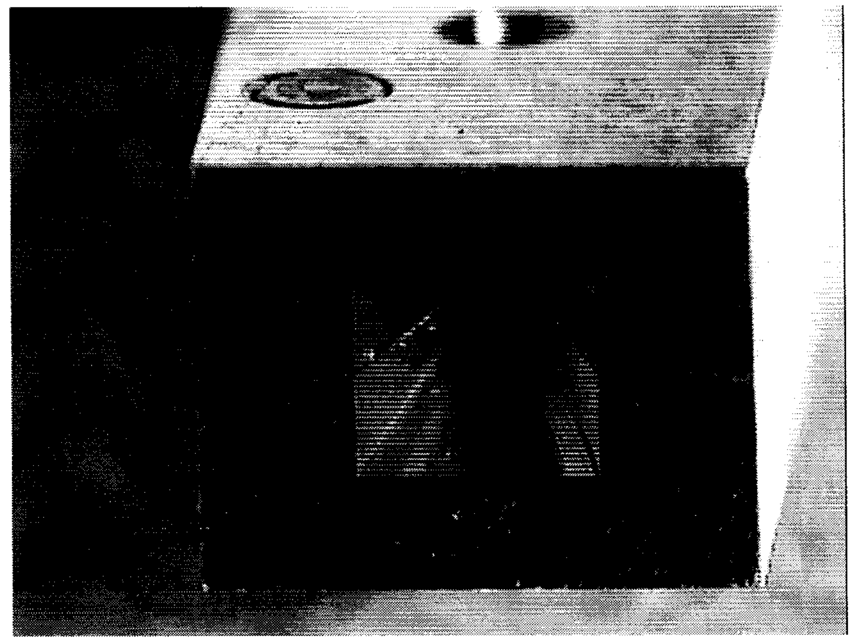


FIELD DISTRIBUTIONS



FABRICATION OF 640 GHZ CIRCUIT USING PRECISION METAL MACHINING





640 GHz Nanoklystron fabricated using precision machining in metal split block. The smallest feature is the 0.0015" diameter bunching grid hole. The assembled unit with an output waveguide horn is shown on the right.

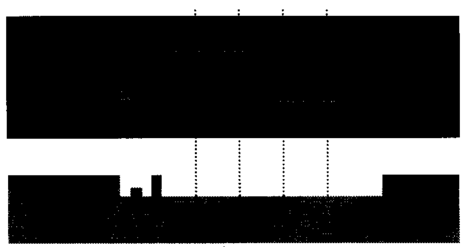
SILICON DEEP REACTIVE ION ETCH WAFER PROCESSING STEPS

Si wafer w/ SJR 5740 ~ 1.5 mm thick

1.

First DRIE step

2.

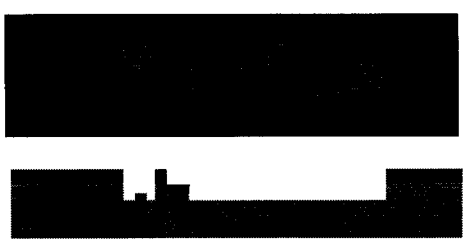


Top view

Side view

Second DRIE step

3.



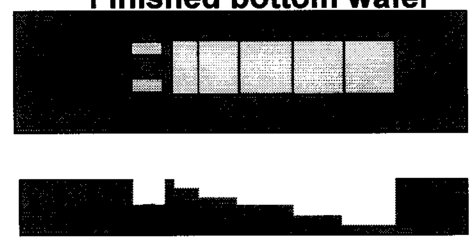
Top view

Side view

-
- **After several similar**
- **DRIE steps...**

Finished bottom wafer

4.

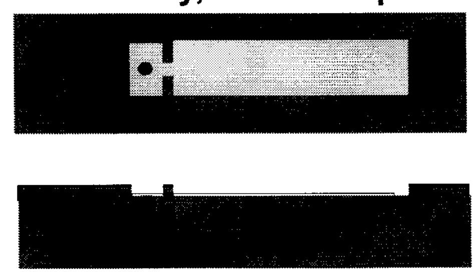


Top view

Side view

Similarly, finished top wafer

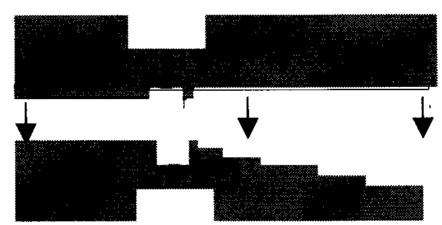
5.



Top view

Side view

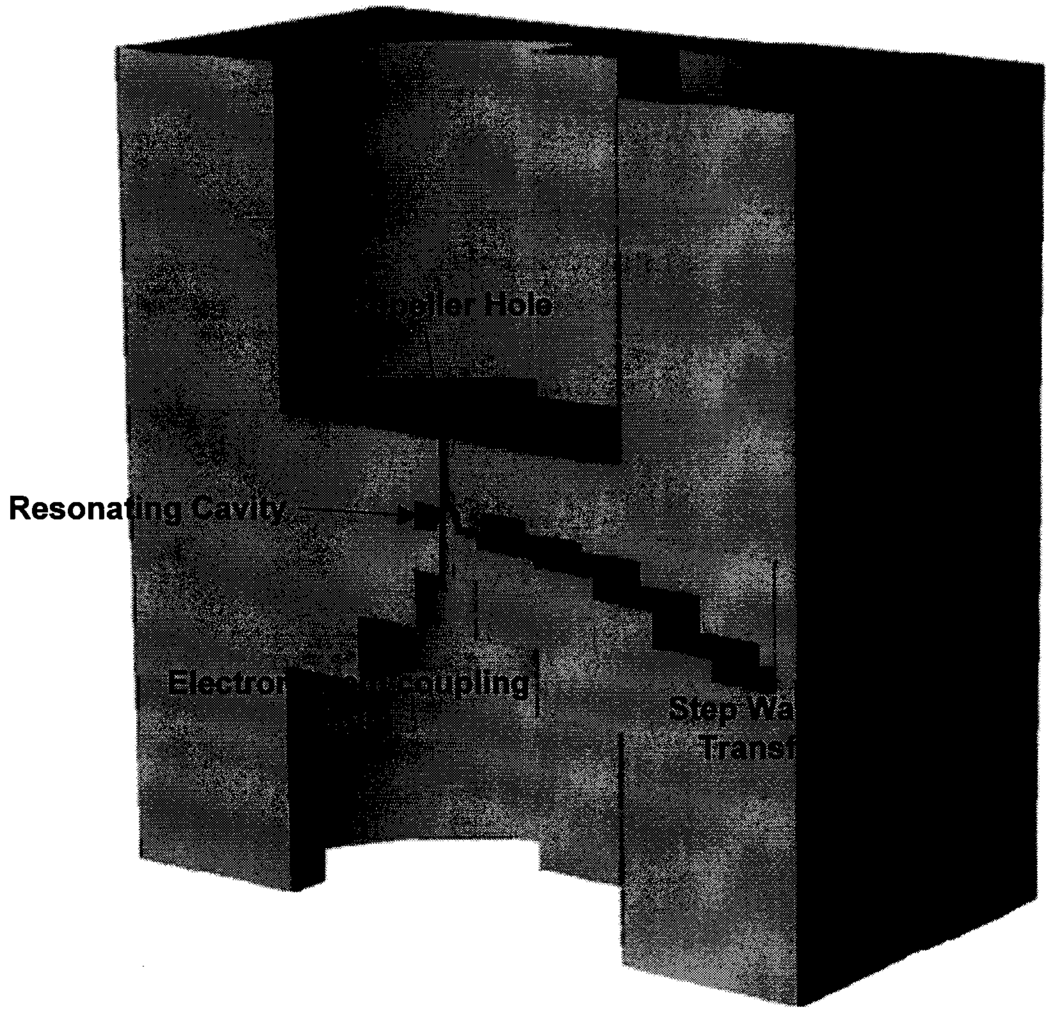
6. **Backside DRIE to create feed through holes, wafer bonding & finally, dicing to produce finished device (side views shown here)**



Top Wafer Side view

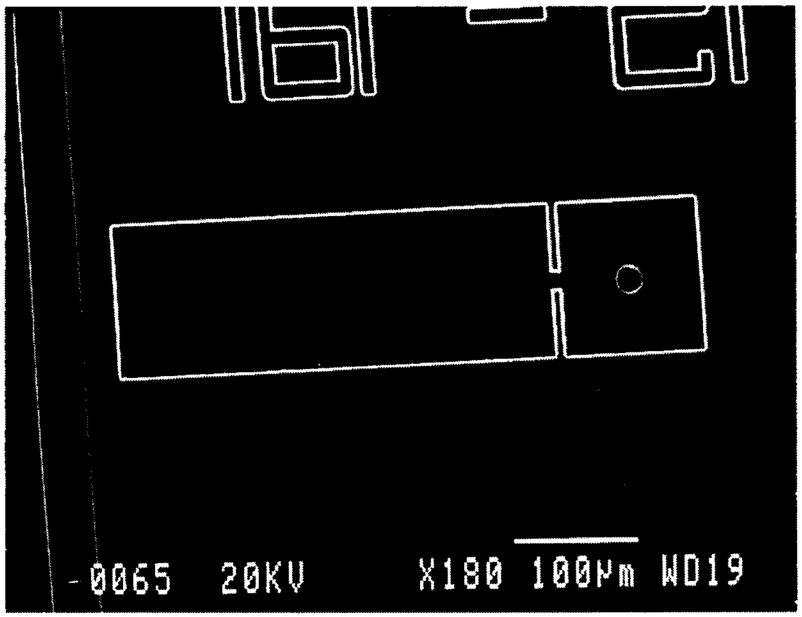
Bottom Wafer Side view

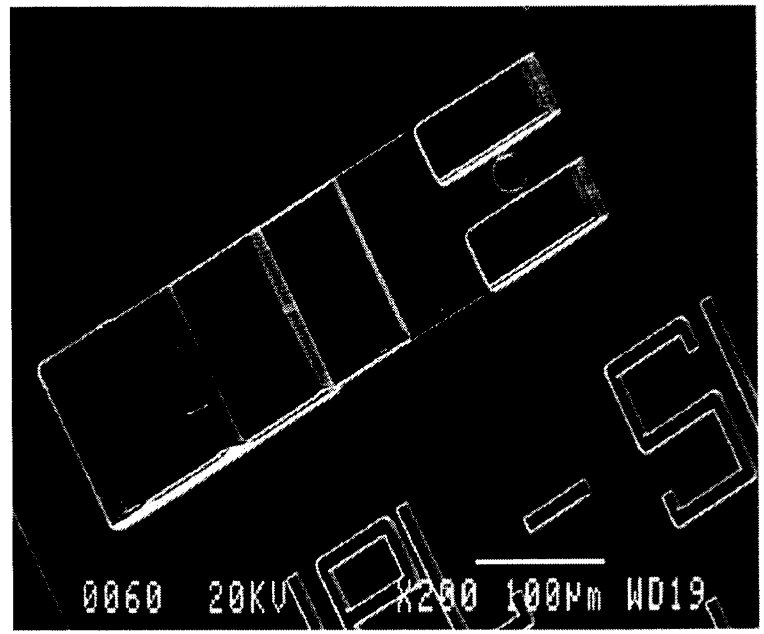
CUT-VIEW OF A WAFER BONDED NANOKLYSTRON (A MODEL)



1st ITERATION MONOLITHIC NANOKLYSTRON CAVITY

[1200 GHz cavity split into two halves]

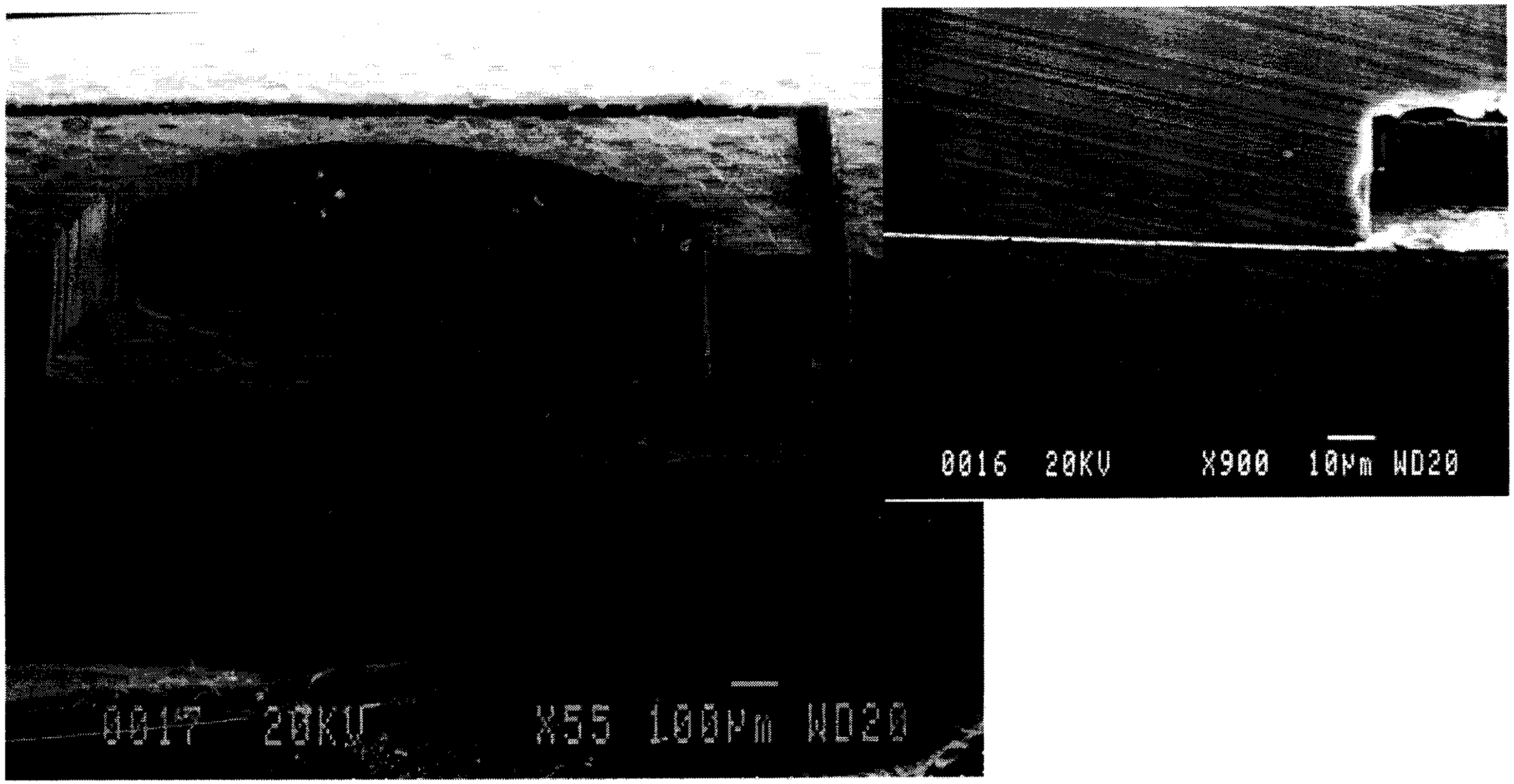




Top half micromachined in silicon showing a repeller hole

Bottom half of in silicon showing an emitter hole and a 5-step waveguide transformer terminating in a silicon window

BONDED WAFER HALVES WITH CAVITY CUTAWAY



Wafer bonded cavity and a magnified view of the bonded interface showing fused gold layers of the top and the bottom halves

DEVELOPMENT OF COLD EMITTER CATHODES

❖ **Electron source for nanoklystrons must be capable of generating current densities of at least 1000 A/cm^2 at low operating voltages.**

❖ **Such current densities can be generated by employing cold cathodes, especially carbon nanotube-based field emitters.**

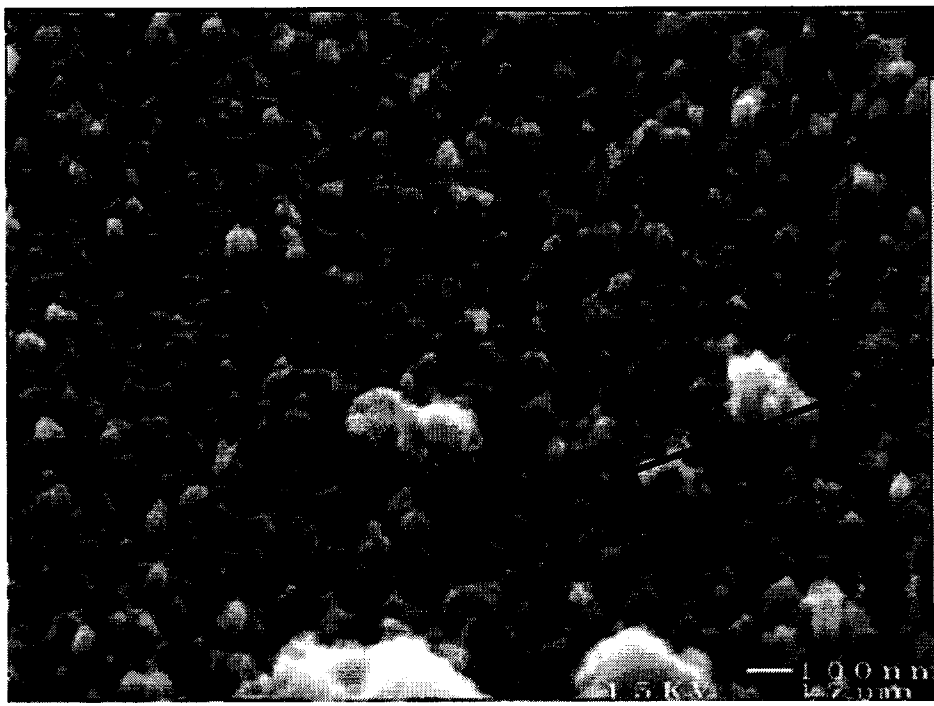
❖ **The small diameter of carbon nanotubes (diameter of a single single-walled-nanotube can be <1 nm) enables efficient emission at low fields, despite their relatively high work function (>4.5eV).**

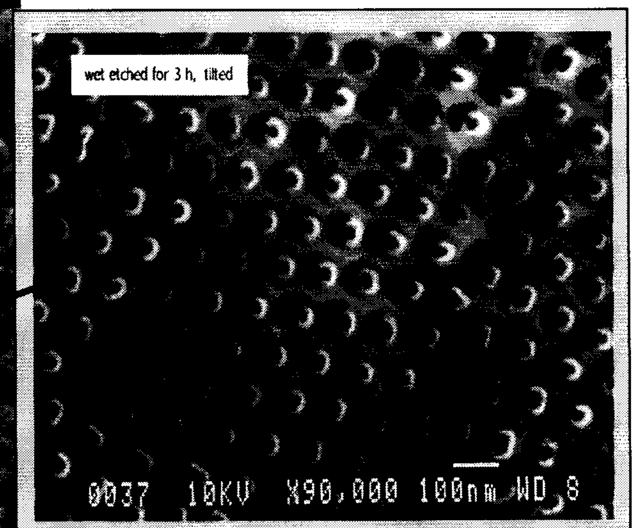
❖ **At 1-3 V/μm of threshold voltage, carbon nanotubes are the best suited for low-power, high-current density applications.**

Efforts are underway to develop flat bed of grid-integrated ordered arrays of carbon nanotubes and tailor their field emission to suit nanoklystron applications.

ORDERED ARRAYS OF CARBON NANOTUBES

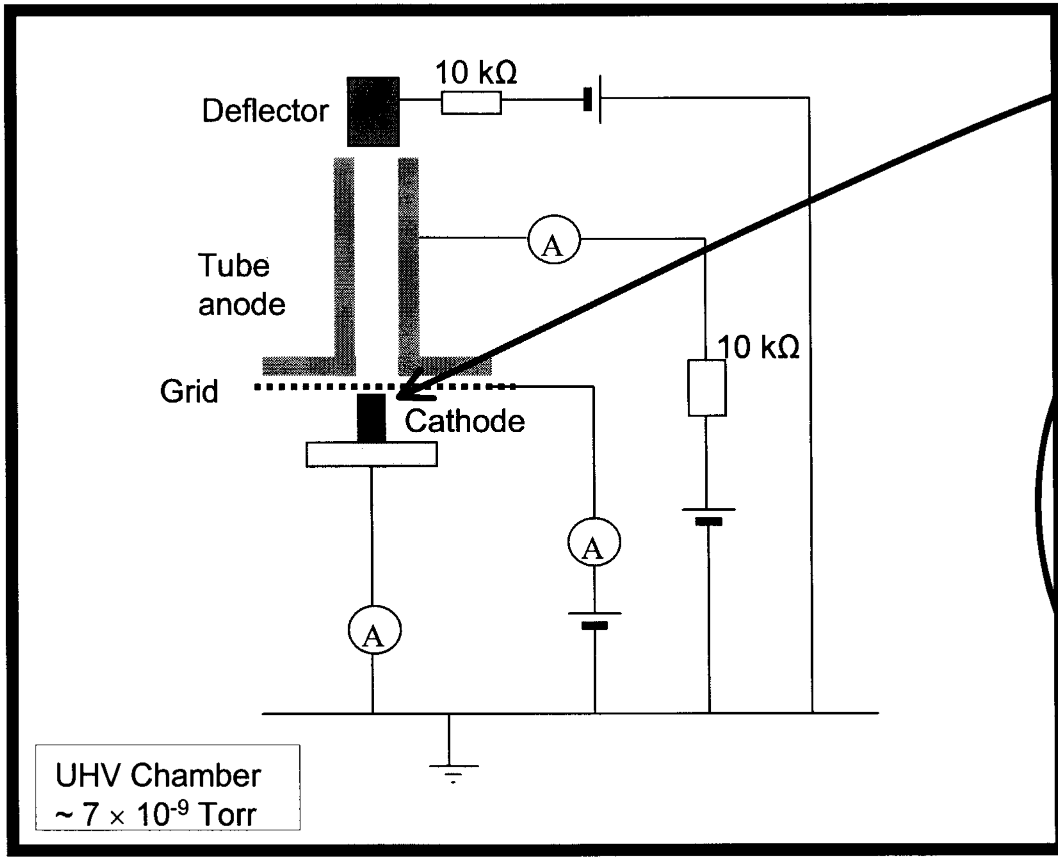
(Nanotubes grown on aluminum-deposited silicon wafer)



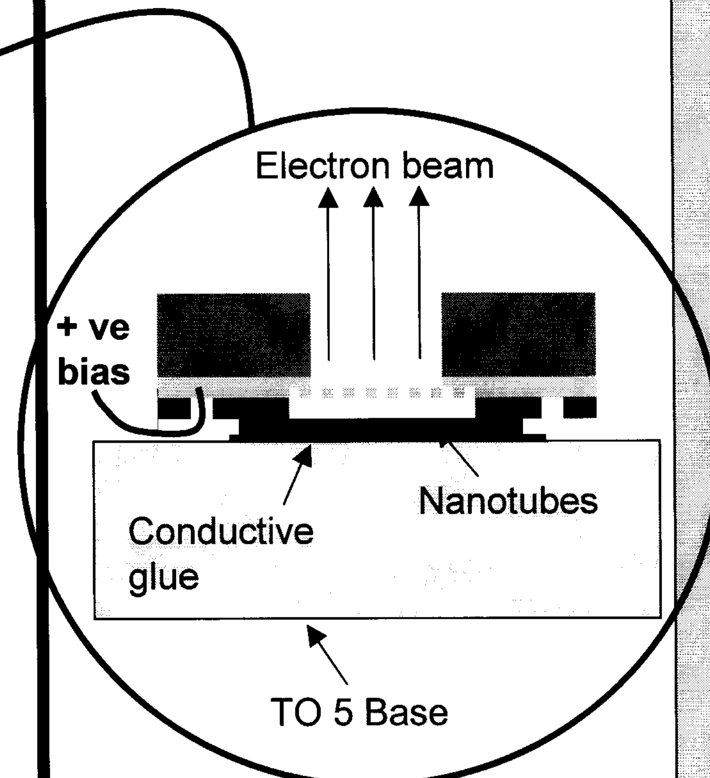


- ❖Nanotubes exposed after ion-milling the anodized pores of alumina
- ❖Tube diameter is typically 40 nm with a density of ~100 tips/μm^2

FIELD EMISSION MEASUREMENTS

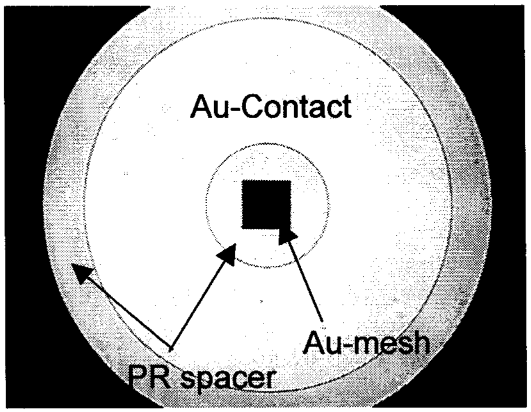


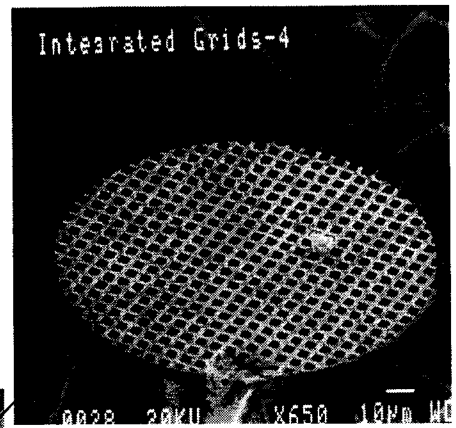
Distance from top of the sample to anode is 2 mm vertically and 5 mm horizontally.

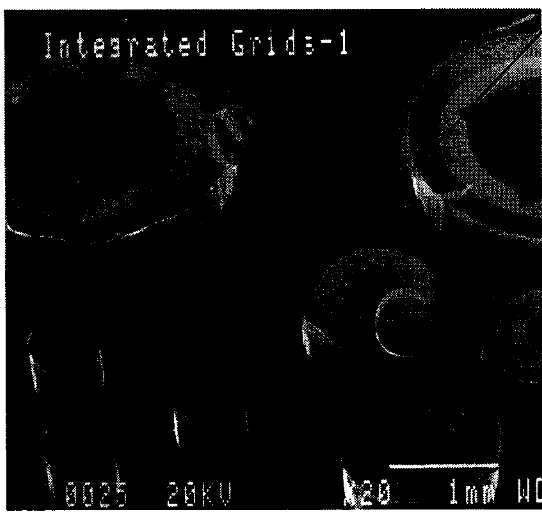


Micromachined grid with nanotubes for field emission measurement

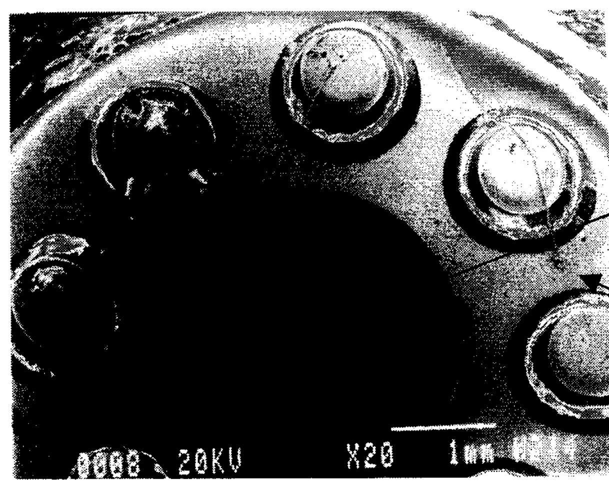
SILICON MICROMACHINED GRID STRUCTURES WITH INSULATING PHOTORESIST SPACER FOR MICRON SEPARATION







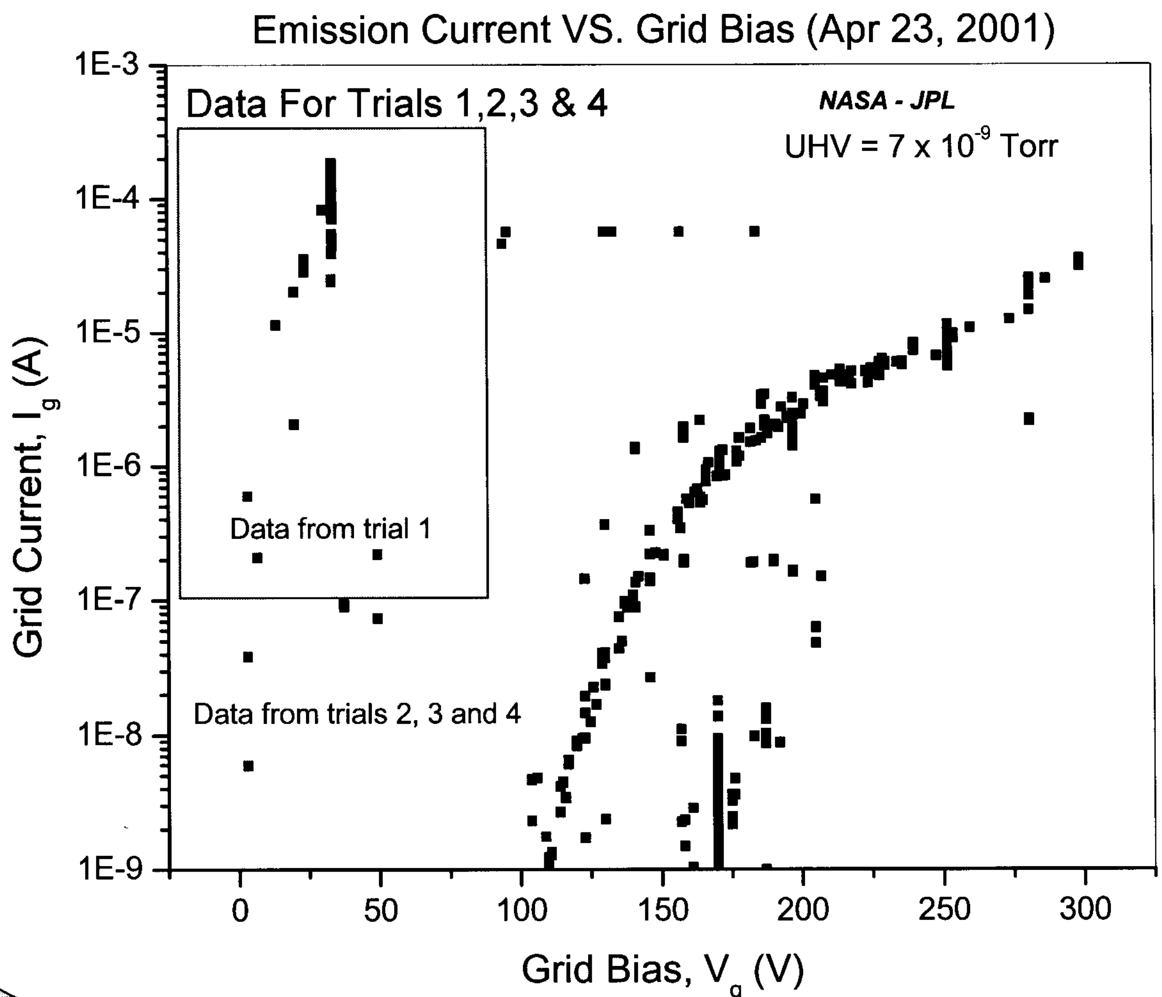
Assembly for field emission measurements



Emission hole made using DRIE

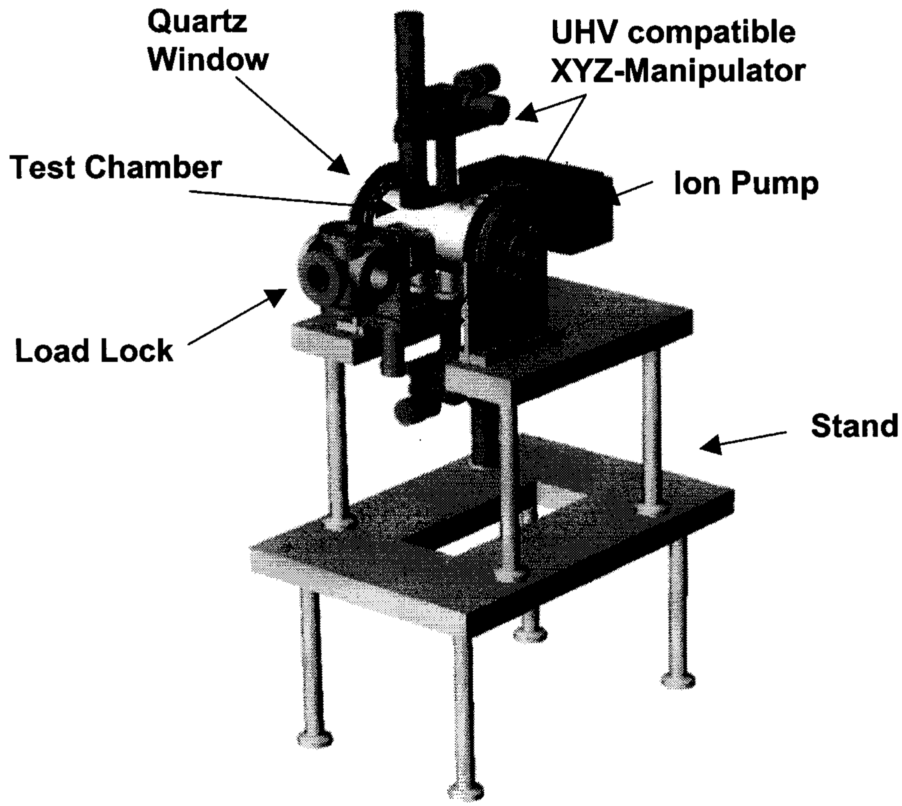
TO 5 Base

ORDERED CNT ARRAY EMISSION MEASUREMENT



Grid area=0.0078 cm^2
#tips=100/μm^2=10^{10}/cm^2
Equiv. Current density=.01A/cm^2
Typical current/tip=300nA
Estimated number emitters=300 for 100μA
Number of tips total=7.8*10^8

NEW NANOKLYSTRON AND EMISSION TEST CHAMBER



SUMMARY

- ❖Design concept, circuit layout & simple analysis of a 1200 GHz nanoklystron presented
- ❖New style ridged waveguide re-entrant cavity designed and analyzed
- ❖Simple cathode/grid field emission tests performed in existing chambers.
- ❖New assembly/measurement chamber being built.
- ❖Close-in cold cathode emitter grid developed for carbon nanotube arrays
- ❖Copper 640 GHz nanoklystron cavity completed.
- ❖First iteration silicon monolithic 300/600/1200 GHz nanoklystron cavities completed. Wafer bonding tests successful.